3.2 High-Heat-Load Optics

The daunting task of developing high-quality x-ray optics to withstand the formidable heat loads produced by insertion devices at the APS has been addressed by a considerable XFD/UPD research effort over the last decade. This effort has paid significant dividends, and the optics developed in this program can handle the heat load from two APS undulators operating at closed gap. We continue to pursue several high-heat-load-related projects, including refinement of monochromator designs (in particular to get better vacuum performance from cryogenically cooled silicon monochromators) and to develop high-heat-load (HHL) multilayer optics for use with undulators. In addition, the staff involved in the high-heat-load program is stepping up research efforts in other x-ray optics areas, including the development of x-ray interferometers and phase-contrast imaging techniques.

3.2.1 Cryogenically Cooled Silicon Monochromators

The use of cryogenically cooled silicon monochromators on undulator beamlines has become routine at the APS. To provide for a better understanding of the limits for this technology, we have measured the performance limits of two such monochromator designs. The results provide quantitative data that can be used to predict the performance of x-ray cryogenic monochromators under increased heat-load conditions that may occur with enhanced APS operations (e.g., higher storage-ring currents or use of longer insertion devices).

Schematics of the tested crystals are shown in Fig. 3.9 (direct cooling) and Fig. 3.10 (indirect cooling). In this context, “direct

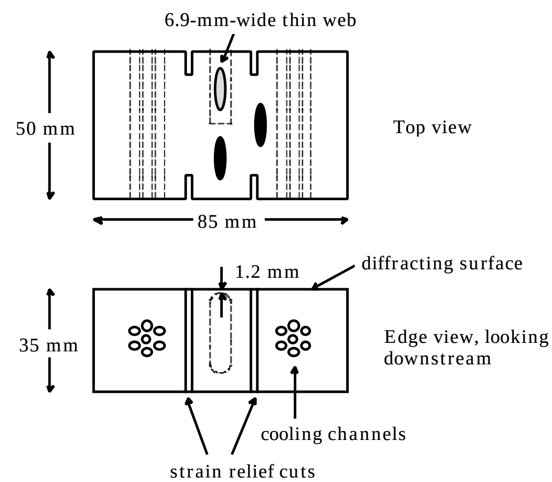

Fig. 3.9. Schematic of the directly cooled silicon monochromator crystal. The diffraction planes are (111).

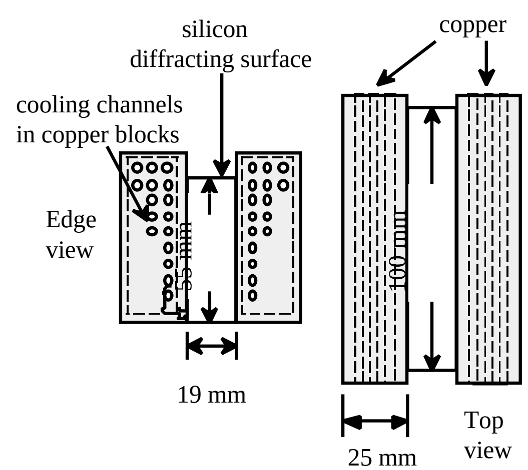

Fig. 3.10. Schematic of the indirectly cooled silicon monochromator crystal. The diffraction planes are (111).

cooling" refers to a monochromator in which the coolant (in this case liquid nitrogen) is in direct contact with the crystal. An "indirectly cooled" monochromator is one in which the crystal is in contact with an intermediary part(s) that is in contact with the coolant.

Special arrangements were made with APS Operations for the use of two standard APS undulators for the directly cooled crystal-monochromator experiments. The standard 1-ID configuration of one APS undulator A was used for the indirectly cooled monochromator. In both cases, calorimetry was performed to experimentally measure the power incident on the crystal. The thermally induced crystal distortion was measured by looking at the full-width, half-maximum (FWHM) widths from double-crystal rocking curves using the Si (333) reflections. For the directly cooled crystal, measurements were performed on both the thin web (see Fig. 3.9) and the thick parts of the crystal.

During the experiments, data were taken for many different x-ray energies with a variety of power densities and power levels. A parametric plot of the data showing total absorbed power and absorbed power density in the first 10 microns of the crystal surface reveals the limits of perfect-crystal performance. Figure 3.11 summarizes the data for the thick and thin part of the directly cooled crystal and shows similar data for the indirectly cooled crystal. The three black traces are drawn, based on experimental data, to denote the acceptable (less than 2 arc seconds of thermal distortion) and unacceptable operating regions. The acceptable regions are to the left and below these lines. The thin blue (100 mA) and thick red (200 mA) lines show the traces of total absorbed power and average absorbed power density in the first 10 μm of a thick crystal for different monochromator energies (7-20 keV) with the corresponding undulator settings (i.e., either the first or third undulator harmonic was matched to the monochromator energy). These "heat-load-tuning-curves" are for 1.5 mm horizontal by 0.5 mm vertical white-beam slits That are about 27 m from the source. This corresponds to the FWHM of the undulator radiation central cone.

These results clearly show that, for the directly cooled crystal shown in Fig. 3.9, the thick part of the crystal performs much better than the thin part. Although the thick part absorbs more power, it has better thermal-conduction paths for heat dissipation. The results also show that the power-absorption profile as a function of depth in the crystal is an important consideration. This is especially true at third-generation synchrotron sources where the critical energy is relatively high. This can be seen from the data plots—at the same total absorbed power, the measured widths are larger for higher absorbed power density in the first 10 μm of silicon.

The results show that this directly cooled monochromator will perform well at thermal loads *twice* the current standard APS operation at 100 mA with a single undulator A (minimum gap of 11 mm) provided the white beam is limited to the size of the undulator central cone. As expected, the performance of the indirectly cooled crystal is not as good as the directly cooled one. Nevertheless, the data show that the

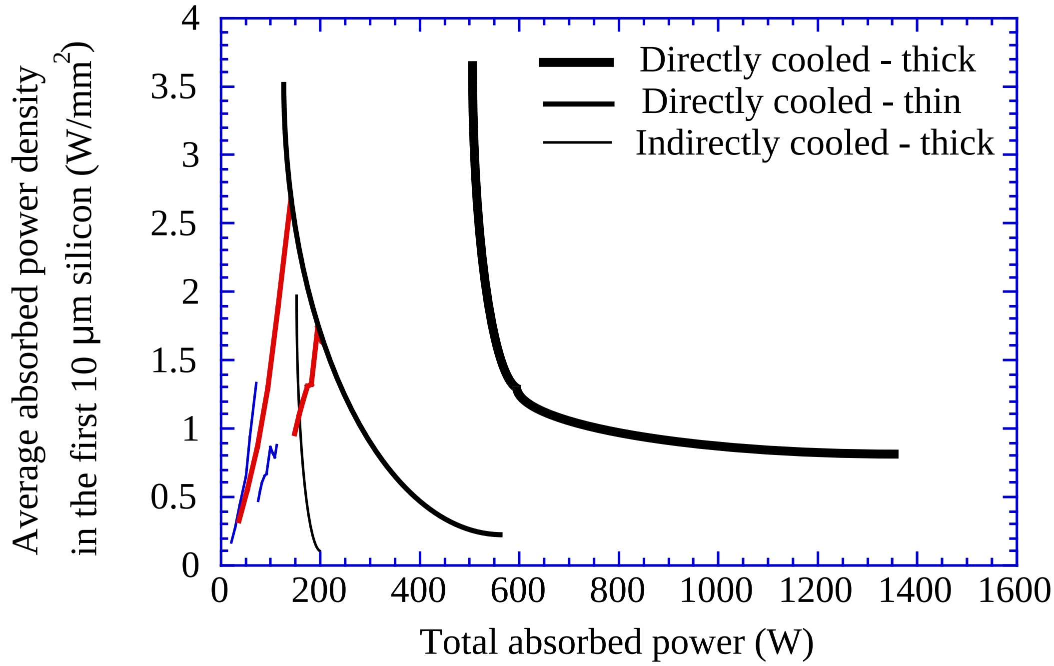

Fig. 3.11. Operating parameters of cryogenically cooled silicon crystals used in the high-heat-load monochromators, which are subject to varying total power and power density as a function of energy, undulator gap, and slit size used. Since diffraction takes place in the first 10 micrometers, the absorbed power density in this region is plotted against total power incident on the crystals. Two different cooling mechanisms, direct cooling with liquid nitrogen flowing inside the crystal and indirect cooling, where the coolant is not in contact with the crystal but with its base, were tested. The lower left part of each curve indicates the region where the measured rocking curve widths were less than 10 microradians, comparable to the vertical divergence of the incident beam. The indirectly cooled thick crystal does not perform well above 160 watts of total power, whereas a directly cooled thick crystal can operate safely up to 500 watts. The thin, directly cooled crystal (which is built into the models prepared for these tests) does not perform as well as the adjacent thick parts, mainly due to difficulties in removing the heat and to mounting strains. For comparison, "heat-load-tuning-curves" are shown for 100 mA (thin blue) and 200 mA (thick red) ring current, with white-beam slits (located at about 27 m from the source) of 1.5 mm horizontal by 0.5 mm vertical.

indirectly cooled crystal can perform well with a single undulator at 100 mA, with the same proviso about white-beam sizes as given above.

3.2.2 Diamond High-Heat-Load Tests

An alternative to cyrogenically cooled silicon for HHL monochromators is the use of diamonds. One figure of merit that is commonly used to evaluate crystals for HHL performance is the ratio of thermal conductivity (k) to thermal expansion coefficient (α). Liquid-nitrogen-cooled silicon and water-cooled diamond crystals have a α/k ratio roughly 40 times greater than that of room temperature silicon.

We have tested a double-crystal diamond monochromator (both diamonds in Bragg geometry) in a similar manner to the tests on cryogenically cooled silicon (i.e., using both single undulators and two standard APS undulators in tandem). The maximum power incident on the monochromator was 280 W for a single undulator and 700 W for the double-undulator configuration. The diamond first crystal straddled a 3-mm-wide trough in a water-cooled copper holder, with a thin layer of Ga/In eutectic between the diamond and the nickel-plated holder to ensure good thermal contact. For the tests with the double-undulator, we used synthetic type IIa, (111) plates manufactured by Sumitomo. These plates were 10 mm by 5 mm by 0.5 mm thick, with mosaic spread of 3 to 4 arcseconds over the whole plate and 1-3 arcseconds under the beam footprint.

To gauge the performance of the monochromator, we measured the width of the double-crystal rocking curve for the (111) and (333) reflections as a function of the power and power density absorbed by the diamond first crystal. We took data at a fixed gap of 11 mm and varied the absorbed power and power density by changing the monochromator energy. We also measured the response when both the energy and the gap were changed in conjunction so that either the first or third harmonic of the undulator radiation corresponded to the monochromator energy. Figure 3.12 shows the FWHM of the (111) double-crystal rocking curve as a function of energy for one undulator and for two undulators at 11 mm gap. The deviation of the single undulator data from theory is due to the mosaic spread/strain of the crystals. The double undulator data also shows some added thermally induced mounting strains but no appreciable widening due to thermal strain in the first crystal.

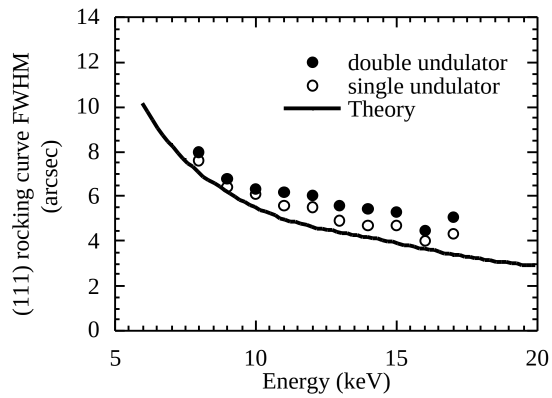

Fig. 3.12. FWHM of the (111) double-crystal rocking curve as a function of energy for one and two undulators at 11 mm gap.

The maximum power and power density absorbed by the first crystal were 37 W and 4.3 W/mm^2 with a single undulator, and 140 W and 17 W/mm^2 for two undulators. Under these conditions, finite element analysis calculations predicted a maximum thermal strain of less than 0.8 and 1.2 arcseconds, respectively, in good agreement with the data. We thus expect that the water-cooled diamond monochromator will perform well under the highest heat-load conditions currently envisaged at the APS.